Tracing protons through the Galactic magnetic field: a clue for charge composition of ultra-high energy cosmic rays.

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We reconstruct the trajectories of ultra-high energy cosmic rays (UHECR) — observed by the AGASA experiment — in the Galactic magnetic field assuming that all particles have the same charge. We then study correlations between the reconstructed events and BL Lacs. The correlations have significance below 10^{-3} in the case of particles with charge +1. In the case of charge −1 the correlations are absent. We interpret this as evidence that protons are present in the flux of UHECR. Observed correlation provides an independent evidence that BL Lacs emit UHECR.

I. INTRODUCTION

Ultra-high energy cosmic rays (UHECR) are a subject of an active debate for over more than 20 years. The data accumulated during this time [1, 2] provide a compelling evidence that the GZK cutoff [3] predicted in the UHECR spectrum at energies $E \sim 10^{20}$ eV may be absent. Many models explaining this puzzle have been proposed (for reviews see Refs. [4]). The actual focus of the debate is the question of whether an unconventional astrophysical model can be constructed which explains the observed super-GZK events, or a new physics is required. This key question still remains open.

With the accumulation of the high-energy events important signatures emerge which discriminate efficiently between different models. It has been known for some time that UHECR events form clusters [2, 5, 6]. Recent analysis shows that clustering is statistically significant [7]. The small angular size of clusters of order $\simeq 2.5^\circ$, consistent with the experimental angular resolution, suggests that they are due to point sources. The models which do not reproduce this feature are therefore disfavored.

Observation of clusters implies that some sources of UHECR may be identified. Recently, significant correlations of arrival directions of UHECR with positions of BL Lacertae (BL Lacs) were found [8]. BL Lacs are blazars (ANGs with relativistic jet directed along the line of sight) characterized in particular by the (near) absence of the emission lines. The correlations between UHECR and BL Lacs are most significant at angles of order $\sim 2.5^\circ$ and are present at relatively low energies $E > 2.4 \times 10^{19}$. Such tightness suggests strongly the existence of neutral primary particles. Association with *distant* BL Lacs combined with *neutrality* of primaries rules out most of the models of UHECR, leaving the models based on neutrino [9] (the Z-burst models), models with hypothetical “immune messengers” [10], or models involving violation of the Lorentz invariance [11]. It should be noted that ultra-high energy photons also cannot be excluded at present [12].

Regardless of whether there exist neutral primary particles, correlations with BL Lacs imply that the acceleration mechanism of UHECR production actually works. Therefore, protons are involved and should be present in the UHECR flux at energies around or below the GZK cutoff. If identified, such protons provide independent evidence that BL Lacs are indeed sources of UHECR. The purpose of this paper is to address this issue.

Knowing actual sources of UHECR is an extremely powerful tool even when statistics is limited. As we will see shortly, this tool can be used to study charge composition of UHECR. The idea is to use the bending of charged primary particles in the Galactic (GMF) [15] and extragalactic (EGMF) [16] magnetic fields. While deflections in EGMF are random and therefore unpredictable, deflections in GMF are regular. If charges, energies of particles and GMF are known, the original directions (before entering GMF) can be restored. If the effect of EGMF is small, the actual positions of sources can be reconstructed.

In practice, one has to solve the inverse problem: to reconstruct charges assuming set of potential sources. We show that this is possible at least in a statistical sense: assuming that a substantial fraction of UHECR are protons significantly improves correlations with BL Lacs. This *implies* simultaneously that GMF model is roughly correct, and that the effect of EGMF is small.

The paper is organized as follows. In Sect. II we briefly review the present knowledge about the Galactic magnetic field and fix the GMF parameters for further calculations. In Sect. III we analyse correlations between BL Lacs and UHECR when the latter are assigned non-zero charges. Sect. IV contains discussion and concluding remarks.

II. GALACTIC MAGNETIC FIELD

The Galactic magnetic field can be divided in two parts: the disc and the halo. Each one has regular and turbulent components. While the strength of turbulent

component is larger, it is the regular field which gives dominant contribution into CR propagation. Most of the information on the regular component of the disc is obtained from the Faraday rotation measurements of pulsars and extragalactic radio sources. The latter are used also for the reconstruction of the halo field. Magnetic field in the disc resembles the spiral structure of our Galaxy. It may either reverse direction between different spiral arms (bisymmetric, or BSS model), or there may be no reversals (axisymmetric, or ASS model). Several field reversals were detected [17, 18, 19, 20, 21] which are consistent with BSS model (note however that discrimination between the two models is complicated by small-scale irregularities in the magnetic field). In our calculations we adopt the BSS model. Simple analytical representation of the spiral field structure (see Refs. [18, 22]) contains the following parameters:

- Distance from the Sun to the Galactic center, $R = 8.5$ kpc.
- Local (at the Sun position in the Galaxy) field strength, B_0.
- Pitch angle p which determines the direction of the local magnetic field (the field points in the direction $l = 90 + p$ in the Galactic coordinates).
- Distance d to the first field reversal. Negative d means that nearest reversal occurs in the direction to the Galactic center, positive corresponds to the opposite direction.

In terms of these parameters the field in the disk is written as

$$B_\theta = B\,\cos(p), \qquad B_r = B\,\sin(p).$$

The magnitude $B = B(r,\theta)$ has the spiral structure,

$$B(r,\theta) = B(r)\;\cos\left(\theta - \beta\ln\left(\frac{r}{R}\right) + \phi\right)\,, \tag{1}$$

where $\beta \equiv 1/\tan(p)$, a constant phase ϕ is given by

$$\phi = \beta\ln\left(1 + \frac{d}{R}\right) - \frac{\pi}{2}\,, \tag{2}$$

and

$$B(r) = B_0\,\frac{R}{r\cos(\phi)}\,. \tag{3}$$

In the last expression the standard assumption that magnitude of the field decreases as r^{-1} in radial direction is made. It is also assumed that $B(r) = \text{const}$ at $r < 4$ kpc. Note that precise dependence of the disc field far away from the Sun position is not important for our study as only a small fraction of the observed UHECR passes through this region. Note also that the constant phase ϕ can be absorbed in another parameter r_0, so that Eq. (1) becomes $B(r,\theta) = B(r)\cos(\theta - \beta\ln(r/r_0))$, which is the parametrization used in Refs. [18, 22]. We find it more convenient to work with parameters directly related to the local field.

To proceed, we need to fix the parameters B_0, p and d. All studies of GMF based on pulsar and extragalactic rotation measures converge on $B_0 = 1.4\,\mu$G, see [17, 18, 19, 21] and recent reviews [23, 24]. We adopt this value.

Pitch angle was found to be close to zero or positive in early publications, $p = +5^\circ$ [25], $p = -2^\circ$ [17], but decreased in more recent studies: $p = -8^\circ$ was obtained in Refs. [18, 19, 20, 26], while in Ref. [21] $p = -15^\circ$ was found as an average pitch angle in nearby spiral arms. Following reviews [23, 24] we take $p = -8^\circ$.

Field reversal was found to be at $d = -0.2 - 0.3$ kpc in Ref. [18] (however, the best fit value of r_0 in the same paper corresponds to $d = -0.48$), at $d = -0.4$ kpc in Ref. [17], at $d = -0.6$ kpc in Refs. [21, 25, 27]. Finally, in the review [23] $d = -0.6$ kpc was cited, while the review [24] follows Ref. [18]. We take $d = -0.5$ kpc.

The simplest approximation for the halo field is obtained by taking the disk field and extending it outside of the disk with exponentially decreasing amplitude,

$$B(r,\theta,z) = \exp\left(-\frac{|z|}{h}\right)\;B(r,\theta)\,. \tag{4}$$

This introduces one more parameter, the height h. Small values of $B_z = 0.2\mu$G found in [18] for the halo field support this approximation. The disc has a height of $h = 1.5$ kpc according to reviews [23, 24] and we adopt this value.

In addition, the halo fields above and below the disk (more precisely, its parts parallel to the disk) may be parallel or anti-parallel. In the latter case the halo field may be approximated by

$$B(r,\theta,z) = \mathrm{sign}(z)\;\exp\left(-\frac{|z|}{h}\right)\;B(r,\theta)\,. \tag{5}$$

The first case, Eq. (4), corresponds to the quadrupole-type model which we denote $\mathrm{BSS_Q}$, while the second case, Eq. (5), corresponds to the dipole-type model denoted as $\mathrm{BSS_D}$ in what follows. There are indications in favour of the $\mathrm{BSS_D}$ global structure [23, 24, 28] of the halo field.

In calculations of UHECR propagation in GMF, the parameters of the latter are often chosen following early work [14]. We do not use the conventions of Ref. [14] because they are ambiguous: the parameter r_0 used there does not correspond to the cited local field strength, the value of pitch angle does not correspond to cited direction of the local field and references for the assumed value of the halo height are not given.

To summarize, we adopt Eqs. (1-5) for the Galactic magnetic field with the following set of parameters

$$\begin{aligned} B_0 &= 1.4\,\mu\mathrm{G} \qquad & p &= -8^\circ \\ d &= -0.5\,\mathrm{kpc} \qquad & h &= 1.5\,\mathrm{kpc} \end{aligned} \tag{6}$$

and assume that this field extends to $R_{\max} = 20$ kpc in all directions. It should be stressed that these parameters

are chosen on the basis of rotation measurements and their choice has nothing to do with the propagation of UHECR.

III. CORRELATION ANALYSIS

We start by specifying the sets of BL Lacs and UHECR. Following Ref. [8], we take BL Lacs form the QSO catalog [29] which contains 306 confirmed BL Lacs. The choice of UHECR set is motivated as follows. Apriori, best results should be achieved with the largest set having best angular and energy resolution. In addition, this should be (relatively) high-energy set, because the uncertainties in the deflection angle (which result from uncertainties in GMF and energies of particles) should not dominate over the angular resolution. This requirement is satisfied at $E > 4 \times 10^{19}$ eV. Therefore, we chose all published AGASA events with energy $E > 4 \times 10^{19}$ eV [2]. This set contains 57 events.

For the quantitative measure of correlations we use the probability $p(\delta)$ introduced in Refs. [7, 8], which is a probability to have certain excess of events within the angle δ from any of the sources (BL Lacs). This probability is calculated by counting how often the excess observed in the real data occurs in the Monte-Carlo (MC) simulations. The MC configurations are generated as described in Refs. [7, 8]. The difference is that now charges are assigned and arrival directions are corrected for GMF both in the real data and in each MC set. The energies of MC events are taken from the real data. Exactly the same treatment of the real data and MC sets is important to prevent appearance of artificial correlations.

The charge assignment can be done by *any* algorithm as long as *the same* algorithm is used in MC simulations. In the simplest case one assigns equal charges to all particles. Although correlations which are due to neutral particles are destroyed in this case, this effect may be compensated by charged particles which move closer to their sources. One may expect this situation when fractions of neutral and charged particles are comparable.

As explained in Ref. [8], there are two possible strategies to estimate the significance of correlations on the basis of $p(\delta)$. One may impose cuts on BL Lac set and adjust them in such a way that correlations are maximum. Likewise, one may look for the "best" values of the parameters of GMF. In this case the penalty factor should be calculated and included in the probability. Since reconstruction of particle trajectories in GMF is rather time-consuming, this approach is not very practical in the case at hand. Thus, we do not adjust the parameters of GMF, Eq. (6), and impose no cuts on BL Lac set except for a single cut in the apparent magnitude. Instead of penalty calculation we present explicit dependence of the probability $p(\delta)$ on this cut. We draw our main conclusions from the behaviour of the curve, rather than from the value of the probability at the minimum.

Correlations found in Ref. [8] were strongest at $\delta \simeq 2.5^\circ$. We therefore fix this value of δ in our calculations. Since δ is not adjusted to minimize the probability, there is no penalty factor associated with that.

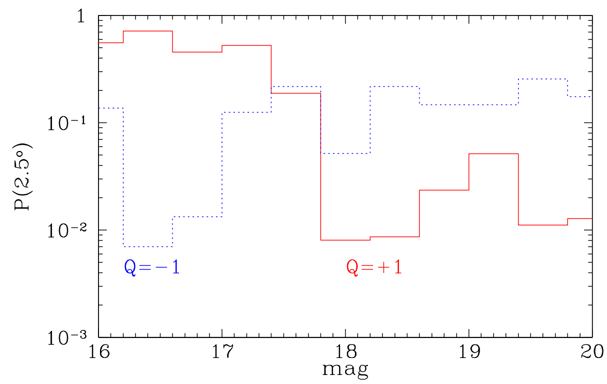

FIG. 1: The dependence of the probability $p(2.5^\circ)$ on the cut in magnitude in BL Lac catalog. Quadrupole-type GMF model, Eq. (4), is assumed.

Consider first the case of the symmetric (quadrupole) model $\mathrm{BSS_Q}$. Fig. 1 shows the dependence of $p(2.5^\circ)$ on the cut in magnitude (the cut mag < 20 corresponds to inclusion of practically all BL Lacs). Solid and dotted lines correspond to the charge $+1$ or -1 assigned to all particles, respectively. We see that in both cases $p(2.5^\circ)$ has minima which are comparable in depth (although both not very deep). One is tempted to conclude that both charges may be present. This kind of situation is expected in the Z-burst models. One may notice, however, that these minima are not equally significant. The minimum at $Q = +1$ is wider and corresponds to much higher statistics (correlations are present at the level of $\sim 1\%$ even when all BL Lacs are included). Moreover, event-by-event analysis shows that 12 out of 14 events contributing to the minimum of probability at $Q = +1$ are situated in the Northern hemisphere. This strange feature suggests that the field in the Southern hemisphere is wrong, while in the Northern one it is roughly correct. The obvious thing to try is the $\mathrm{BSS_D}$ model in which the Southern field has different sign.

Consider the case of the asymmetric (dipole) model $\mathrm{BSS_D}$. In our problem changing the direction of the GMF in the Southern hemisphere to the opposite is equivalent to flipping sign of charges of the events in the Southern hemisphere. According to previous results, this should increase the correlations. Indeed, the situation changes. Fig. 2 shows the dependence of the probability $p(2.5^\circ)$ on the cut in magnitude in the case of the $\mathrm{BSS_D}$ model. Three cases $Q = -1, 0, +1$ are shown. The correlations in the case $Q = +1$ have improved by almost two orders of magnitude as compared to the $\mathrm{BSS_Q}$ model and are now at the level below 10^{-3} in a wide range of magnitudes. Even with no cuts on BL Lacs the significance of correlations at $Q = +1$ is below 10^{-3}. On the contrary, in the case $Q = -1$ the correlations are now absent. In the case

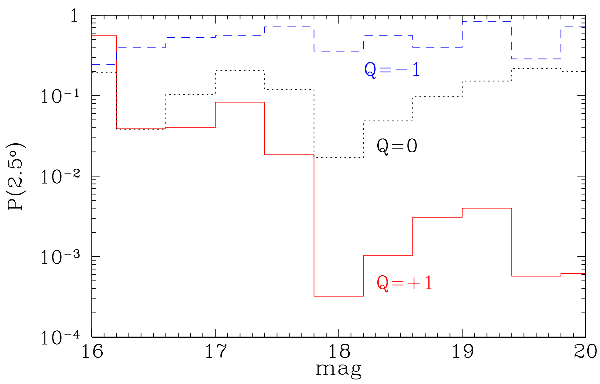

FIG. 2: The dependence of the probability $p(2.5°)$ on the cut in magnitude in BL Lac catalog. Dipole-type GMF model, Eq. (5), is assumed.

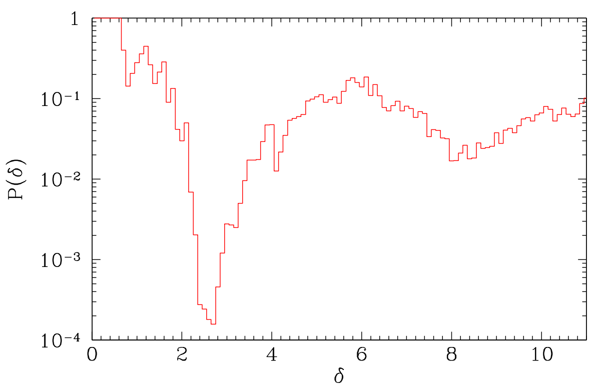

FIG. 3: The dependence of the probability $p(\delta)$ on the angle δ (in degrees) with the cut mag < 18 in the BL Lac catalog and charge $Q = +1$. Dipole-type GMF model, Eq. (5), is assumed.

$Q = 0$ correlations with BL Lacs satisfying mag < 18 are observed at the level of 2%. For completeness, Fig. 3 shows the the dependence of $p(\delta)$ on the angle δ at the cut mag < 18.

IV. DISCUSSION AND CONCLUSIONS

The pairs BL Lac – cosmic ray separated by less than 2.5° are listed in Table I (imposing the cut mag < 18). BL Lacs appearing in this table are probable sources of UHECR. For each BL Lac the name, Galactic coordinates l and b, and redshift z (when known) are given. Corresponding cosmic ray energy E (in units of 10^{19} eV) and probable charge Q are listed in the last two columns.

We have assigned $Q = 0$ to those particles which contribute to correlations at $\delta = 2.5°$ in the case when all particles are assumed to be neutral. Likewise, we have assigned charge $Q = +1$ to those events which fall within 2.5° from any of the BL Lacs when they are assumed to have charge +1 and deflection in GMF is taken into account. Some events satisfy both requirements; corresponding entry in Table I reads "0 or +1".

	Name	l	b	z	E	Q
1	2EG J0432+2910	170.52	-12.6	-	5.47	0 or +1
2					4.89	0 or +1
3	RX J1838.7+4802	76.95	21.83	-	10.6	0 or +1
4					4.35	+1
5	RGB J0109+182	128.82	-44.4	-	21.3	+1
6					5.07	0 or +1
7	RX J1058.6+5628	149.59	54.42	0.144	7.76	0
8					5.35	0
9	RGB J1415+485	91.2	63.11	-	6.22	+1
10	RX J0035.2+1515	117.15	-47.44	-	5.53	0 or +1
11	RX J1704.8+7138	103.09	33.96	-	4.78	+1
12	OT 465	74.22	31.4	-	4.88	0 or +1
13	RX J1702.6+3115	53.4	35.76	-	4.47	0 or +1
14	RX J1359.8+5911	107.36	55.83	-	4.46	0
15	RGB J0159+107	148.75	-48.64	-	4.2	+1
16	1ES 1853+671	97.74	24.63	0.212	4.39	+1
17	RX J1100.3+4019	175.87	63.56	-	7.21	0
18	EXO 1118.0+4228	167.85	66.16	0.124		0 or +1
19	RGB J1426+340	57.6	68.53	-	4.97	+1
20	TEX 1428+370	63.95	66.92	0.564		+1
21	B2 0804+35	186.48	30.35	0.082	4.09	+1
22	TXS 0806+315	190.42	29.36	0.22		+1

TABLE I: The list of pairs BL Lac – cosmic ray which contribute to correlations of Fig. 2 at mag < 18.

Lines 1-8 of Table I contain four BL Lacs which correlate with two cosmic rays each. These are most probable sources. In the lines 9-16 eight BL Lacs are listed which correlate with singlets. Finally, lines 17-22 contain three cosmic rays for which sources are ambiguous (each ray has two neighbouring BL Lacs within $\delta < 2.5°$).

Examining Table I one notices two striking regularities (we do not attempt to assign statistical significance to those in the present paper). First, most objects in this table are X-ray selected radio loud BL Lacs. Second, the fraction of BL Lacs with unknown redshifts in Table I is much larger than in average over the whole BL Lac catalog. In doublet part of the Table this fraction is 6:2, in singlet section this fraction is 7:1.

Absence of emission lines (more precisely, their weakness and narrow width) is a defining feature of BL Lac family within the general blazar class. Therefore, it is not surprising that redshifts of roughly half of confirmed BL Lacs are not known. Increased fraction of such BL Lacs in Table I may mean that the absence of emission lines is important for a blazar to became emitter of UHECR.

As it is generally assumed, BL Lacs with unknown redshift may be far away: the observational bias would then explain that the redshifts of such objects are unknown more often. Then however new physics or extreme astro-

physics would be necessary to explain observed correlations.

Within the conventional framework, when propagation is limited by interactions with comic backgrounds, one should expect sources to be relatively nearby. Closest BL Lac with known redshift is at $z = 0.029$. This is well outside of the GZK sphere. It should be noted, however, that most of the cosmic rays in Table I have energies below the GZK cutoff. As it was found in Ref. [12], the flux of protons at energy $E = 8 \times 10^{19}$ is not attenuated substantially if sources are located at $z < 0.03$, and the flux at $E = 5 \times 10^{19}$ is not attenuated if sources are located at $z < 0.1$. Assuming this range of redshifts for charged entries in Table I, we see that there is no problem to explain all of them except lines 3 and 5. The ray (21-22) has sufficiently low energy so that BL Lac B2 0804+35 with z=0.082 can be a source without any problem with attenuation. Likewise, the BL Lac 19 can be an actual source of the ray (19-20) if it has redshift $z \lesssim 0.1$. Thus, the correlations due to charged particles listed in Table I can be explained within the framework of conventional physics if sources with unknown redshifts are assumed to be within $z \lesssim 0.1$.

Consider now the entries corresponding to neutral particles. According to Ref. [12], photons can be UHECR primaries at any energy $E > 10^{19}$ eV provided that EGMF is smaller than 10^{-9} G, energy spectrum at the source is hard, $\propto E^{-\alpha}$ with $\alpha < 2$ and the maximum energy is high enough. (Note that correlations with charged particles imply that EGMF is in this range anyway.) Therefore, entries 3 and 17 can be explained by photons. The real difficulty is with rays 5,7,8 and 16. Note, however, that according to MC simulations, there should be 7 background events in the Table I on average.

To summarize, the idea of using the Galactic magnetic field as a mass-spectrograph of UHECR seems to work. The correlations between UHECR and BL Lacs substantially improve when arrival directions of cosmic rays are corrected for GMF. If not a statistical fluctuation, this implies the following: i) cosmic rays of highest energies contain a substantial fraction of protons ii) extragalactic magnetic fields have little effect on propagation of UHECR even from cosmological distances iii) the model of the Galactic magnetic field described by Eq. (5) is roughly correct.

Finally, the significance of correlations with charged particles is $p < 10^{-3}$. This may be considered as yet more evidence that BL Lacs are sources of UHECR. Interestingly, the events and BL Lacs contributing into the correlation with lowest p found in Ref. [8] and the charged events of Table I do not overlap, so the two correlations should be considered as independent.

Acknowledgments

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